Beagle 2

ESA/UK

Commission of Inquiry

5 April 2004

<u>**Signature page**</u>

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EXECUTIVE SUMMARY

INTRODUCTION

The UK Minister of Science and Innovation and the ESA Director General jointly established a Commission of Inquiry to investigate the circumstances and possible reasons that led to the loss of the Beagle 2 mission.

In formulating its report, the Commission has concentrated on the possible programmatic and technical issues and shortcomings. It provides recommendations for the future, rather than attempting to assign individual responsibilities.

The Commission wishes to thank all institutions, companies and individuals who have participated in the Commission's work for their full cooperation and support.

PROGRAMMATIC ASPECTS

Beagle 2 was the first European lander designed to explore the surface and sub-surface of Mars. It was carried by the ESA Mars Express spacecraft.

A Consortium was formed to undertake Beagle 2 comprising: the Open University (Consortium leader), The University of Leicester, Martin Baker Aircraft Company (MBA), and Matra-Marconi Space (later to become EADS Astrium). They considered Beagle 2 to be an exciting and motivating project. Initially, each Consortium partner funded its own involvement and there was no clear customer-supplier relationship. In the Commission's view, a clear customer-supplier relationship is essential in space projects, regardless of the financial arrangements amongst the partners.

In response to an ESA Announcement of Opportunity, Beagle 2 was proposed as a "scientific instrument", funded by the UK, to be carried on Mars Express. It was given the highest priority amongst the proposed landers by the Peer Review Committee (PRC) of ESA's Science Programme Committee (SPC) on the basis of its excellent scientific potential, notwithstanding the engineering and management shortcomings which had been identified by ESA. The PRC recommended that a number of conditions be met, in particular that full funding was demonstrated by October 1998. This did not happen.

The Commission's assessment is that the concept of treating a planetary lander such as Beagle 2 as a "scientific instrument" on an ESA spacecraft was a fundamental error and that many subsequent problems in the project stemmed from this. Beagle 2 should have been recognised as a complex, innovative spacecraft requiring management by an organisation with relevant experience – this was likely to be beyond the capability of a University-led group. The Commission considers that, in the future, the approach adopted for Beagle 2 must not be repeated.

The SPC approved Beagle 2 in November 1999. At this time the project's estimated Cost At Completion (CAC), excluding lander scientific instruments, was £24M. The finance in place was £6M from the Consortium partners and £5M from the UK Government. The additional funding was expected to come from private sponsors. However, the funding guarantee for the full development, as requested by the PRC, still had not been confirmed.

The lack of guaranteed funding for Beagle 2 during its early stages seriously hindered the orderly build-up of the project engineering team, with the consequence that the design and development activities were delayed, exacerbating an already critical schedule.

The Commission's view is that the SPC should not have confirmed the selection of Beagle 2, given the failure of the project to comply with the recommendations of the PRC.

An independent review of Beagle 2, chaired by J Casani of NASA, took place in September 2000. The report, whilst praising the Beagle 2 team, was highly critical of the project status. Particular concerns were: the complex and fragile management arrangements, lack of mass and schedule margins and lack of robustness in the Entry, Descent and Landing System (EDLS). The Commission's assessment is that insufficient actions were taken to correct the shortcomings identified in the Casani report.

In Sept 2000, the UK authorities invited ESA to join the Beagle 2 partnership. With the new CAC at £35.4M, the ESA SPC agreed to expenditure of 24.2M€ including a contract to Industry for 16M€ covering inter alia the EDLS. ESA and Astrium/MBA were unable to reach agreement on a contract for the EDLS, but a contract was signed based on milestone payments.

In June 2001, MBA announced their intention to withdraw from the project. In the Commission's view the withdrawal of MBA, the designers of the EDLS, was a serious setback that undermined the technical management and oversight of this mission critical system. This lack of support was to prove crucial during the remaining development and testing programme.

In July 2001, the CAC rose to £42.5M, leading to a funding crisis. This was resolved by a Heads of Agreement between the parties, which established ESA as technical advisor to BNSC, and Astrium as the Prime Contractor with a firm-fixed-price contract through The Open University. In the Commission's view, the Heads of Agreement resolved many of the immediate management and funding issues, but did not implement full ESA management. Further, too much time had been lost through piecemeal funding and this exacerbated the critical schedule. This led to an attenuated testing programme to meet the cost and schedule constraints, thus inevitably increasing technical risk.

Failures during the testing of the EDLS air-bags in early 2002 necessitated a re-design and the development of a new main parachute. All partners regarded this as a high-risk development and ESA prepared for the eventuality that Beagle 2 would not be delivered in time for launch. Due to the dedication and hard work of the Beagle 2 team, the probe was delivered to the Mars Express Prime Contractor in February 2003.

The Commission's opinion is that, because of the high profile of Beagle 2 and the public's interest in it, ESA and the UK Authorities should have managed the expectations of the mission outcome in a balanced and objective way. It should have been made clear to all stakeholders, including the public, that the risk of failure was significantly higher than had been anticipated.

The Commission has concluded that there was no single programmatic error which led to the loss of Beagle 2. The following factors however contributed to increased mission risk:

- Treating Beagle 2 as a "scientific instrument" rather than as a complex, innovative spacecraft;
- Lack of guaranteed funding during the early phases of development;
- The withdrawal of MBA, the designers of the EDLS, from the project;
- Lack of an adequate management organisation with the relevant experience;
- Lack of available margins to manage and mitigate risks.

TECHNICAL ASPECTS

The Beagle 2 science payload was carried in a highly-integrated, small spacecraft which provided structural support, thermal control, power, data handling and communications, together with the EDLS. In the Commission's opinion, the very ambitious scientific mission objectives, together with the stringent mass and volume constraints, led to the choice of very innovative, but risky solutions without adequate robustness.

Planetary missions require robust design and engineering, together with sufficient margins of time and resources (mass, volume, power etc.) to permit a proper risk management and mitigation programme. Risk management, in the classical sense, was not possible on Beagle 2.

Furthermore, because of funding and schedule constraints, risks were not adequately mitigated by a thorough test and verification programme.

No functional deployment testing of the EDLS, eg by a high-altitude drop test, and no system-level pyro-shock testing were included in the test programme, primarily for cost reasons. In the Commission's opinion, with the selected design, such tests should have been mandatory.

No system-level requirements, specifications or design report documentation for the complete Beagle 2 mission were generated by the initial Consortium. The lack of such documentation became critical after the departure of MBA.

In the Commission's opinion, the lack of system-level documentation resulted in project reviews being unable to assess the overall system-level design. This resulted in significant technical design and verification issues being overlooked, increasing the risk of mission malfunction or, possibly, mission loss.

The Commission considers that for complex and unique space missions such as Beagle 2, it is essential to engage experts on a world-wide basis to provide advice and review the project, since relevant expertise is not always available in Europe.

Very late in the programme (less than 1 year before delivery) failures of the air-bag drop tests resulted in the need for a new main parachute design. Overall, the Commission's assessment is that the rapid development and testing programme of the main parachute did not lead to an adequate qualification for use on Mars.

From NASA and Mars Express data, it appears that the actual atmospheric conditions prevailing during the Beagle 2 entry and descent deviated from the models used for the design. Independent analyses performed for the Commission indicate that the entry mission design was sufficiently robust to tolerate these variations. Hence the Commission concludes that the deviation in the atmospheric entry conditions is not a probable failure mode for Beagle 2.

In the absence of any data after Beagle 2 separation from Mars Express, the Commission has not been able to identify with certainty any single technical failure/shortcoming which caused mission loss; however, each of the following items individually are credible possibilities:

- Air-bag design not robust and the testing programme not sufficient;
- Risk of collision between the back cover and the main parachute;
- Re-bounding (up to 28mtr) of the air-bag/lander into the main parachute;
- Untimely release of the lander from the air-bag.

RECOMMENDATIONS

These are the recommendations of the Commission for future missions which can be found in the report; referenced to the section in which they occur.

Recommendation 1 (sec. 4.2.2.)
Future lander missions should be under the responsibility of an Agency with appropriate capability and resources to manage it. The lander/orbiter mission should be managed as an integrated whole. Nationally-funded science instruments should be included in the lander on the same basis as on the orbiter.

Recommendation 2 (sec. 4.2.2.)
For future science payloads which are critical to overall mission success or have a very high public profile, the ESA Executive should make a formal, comprehensive assessment of all aspects of proposals including technical, management and finance, and advise SPC accordingly before acceptance. If the assessment is not positive, ESA should advise the SPC not to accept the proposal.

Recommendation 3 (sec. 4.3.2.)
Sponsoring Agencies of nationally-funded contributions to ESA projects should ensure that the required financing is committed at the outset to meet the estimated Cost at Completion and require that a structured development programme is established.

Recommendation 4 (sec. 4.3.2.)
In addition to the ESA-led reviews of interfaces, formal Project Reviews of nationally-funded contributions to ESA missions should be undertaken by the sponsoring Agency to a standard agreed with ESA and should cover the entire project.

Recommendation 5 (sec. 4.4.2.)
When an independent review of a nationally-funded project, such as the Casani review of Beagle 2, is commissioned, it is essential that ESA and the Sponsoring Agency ensure that its recommendations are properly dispositioned and those which are agreed are actioned and followed up through a formal process.

Recommendation 6 (sec. 4.5.2.)
For future projects, Heads of Agreement or similar formal arrangements between cooperating entities, ESA, and national sponsors, should be put in place at the outset of projects and should include formal consultations at key stages of the project to jointly consider its status.

Recommendation 7 (sec. 4.5.2.)
Fixed price contracting should be avoided solely as a mechanism for controlling costs, and used only where the sponsor and contractor are in alignment on the requirements and scope of the work and the sharing of risks between them. Both parties should be confident that the contractor has sufficient margins to manage his uncertainties and risks.

Recommendation 8 (sec. 4.6.2.)
For future high-profile/high-risk projects, ESA and any Sponsoring Agency should manage the expectations of the outcome of the project in a balanced and objective way to prepare for both success and failure.

<u>Recommendation 9</u> (sec. 5.1.1.)
At the start of a programme, the funding authority(ies) should require that there is system-level documentation. This is necessary to provide all partners with the technical requirements for the project and sufficient design description and justification such that the margins and risks being taken in each partner's area of responsibility are visible.

<u>Recommendation 10</u> (sec. 5.2.1.)
Future planetary missions should be designed with robust margins to cope with the inherent uncertainties, and they should not be initiated without adequate and timely resources to achieve that.

<u>Recommendation 11</u> (sec. 5.2.2.)
Future planetary entry missions should include a minimum telemetry of critical performance measurements and spacecraft health status during mission critical phases such as entry and descent.

<u>Recommendation 12</u> (sec. 5.2.3.)
For future planetary entry missions, a more robust communications system should be used, allowing direct commanding of the lander for essential actuations and resets without software involvement - enabling recoveries in catastrophic situations.

<u>Recommendation 13</u> (sec. 5.3.1.)
Planetary probe missions involving high-level shocks from pyros and other events should undergo representative shock environmental testing at system level.

<u>Recommendation 14</u> (sec. 5.3.2.)
Adequate and realistic deployment tests should be performed, and sufficient time and resources must be available in the development of a new planetary mission.

<u>Recommendation 15</u> (sec. 5.4.1.2.)
Elimination of internal connectors for mass saving should be avoided if at all possible. But if unavoidable, a stringent system of check and independent cross-check should be followed during the final wiring operation.

<u>Recommendation 16</u> (sec. 5.4.3.)
A back-up for the entry detection event (T0) must be included in the design of planetary entry probes.

<u>Recommendation 17</u> (sec. 5.4.4.)
Future planetary entry missions should include a release of the back cover and front shield which is aerodynamically stable and analytically predictable to avoid uncontrolled re-contact of front shield with the lander.

<u>Recommendation 18</u> (sec. 5.4.4.)
Sufficient difference between ballistic coefficients of all separated items, eg. back cover assembly and the main parachute, or other positive means, must be ensured to exclude collision after separation.

<u>Recommendation 19</u> (sec. 5.4.7.)
Adequate competencies in air-bag and parachute technology must be available for future European planetary missions, making best use of existing expertise e.g. in USA and Russia.

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1 INTRODUCTION

Beagle 2 was the lander aboard the ESA's Mars Express orbiter mission, which was launched on 2 June 2003 from the Baikonur Cosmodrome. It was scheduled to arrive at Mars on 25 December 2003. Beagle 2 was ejected successfully from Mars Express on 19 December 2003 and commenced its coast, entry and descent towards the surface of Mars. Unfortunately, it has not been possible to communicate with Beagle 2 since its ejection and it was declared a loss.

2 MANDATE AND MODUS OPERANDI

The Beagle 2 Commission of Inquiry was established under a mandate dated 4 February 2004, given in full below, to investigate the circumstances and possible reasons that led to the failure of the Beagle 2 mission.

The report is delivered to the UK Minister for Science and Innovation and the ESA Director General.

2.1 MANDATE

Further to the declared loss of Beagle 2 and the absence of contact since its release from the Mars Express satellite on 19 December 2003, it has been decided to initiate an inquiry on the events, circumstances and possible reasons that led to the failure of the Beagle 2 mission.

To the extent that the development, launch and operations of Beagle 2 lander and the Mars Express satellite concern both UK national authorities and organisations and the European Space Agency, the UK Department of Trade and Industry, represented by Lord Sainsbury, Minister for Science and Innovation and Jean-Jacques Dordain, Director General of the European Space Agency (ESA) have jointly decided to set up a Commission of Inquiry, to be chaired by the Inspector General of ESA.

The Inquiry will address the following aspects:

1. Technical
The Mandate of the Commission is to:
a) assess the available data/documentation pertaining to the in-orbit operations, environment and performance characterisation, and to the on-ground tests and analyses during development.
b) identify possible issues and shortcomings in the above and in the approach used, which might have contributed to the loss of the mission.

2. Programmatic
The Mandate of the Commission is to:
a) analyse the programmatic environment (i.e. decision processes, funding level and resources, management and responsibilities, interactions between the various entities) throughout the development.
b) identify possible issues and shortcomings which might have contributed to the loss of the mission.

The Commission of Inquiry will document its findings in a report with recommendations where deemed appropriate.

The Commission of Inquiry shall be granted access to all relevant documentation within the public organisation and private entities which were involved in the development and in-orbit operations of any element of Beagle 2 and Mars Express (in particular the BNSC partners, Open University, EADS-Astrium, University of Leicester, National Space Science Centre, ESA) and will be able to hold personal interviews with individuals at all levels within those entities, as required. The Commission of Inquiry will have access to expert support, as necessary.

The work of the Commission of Inquiry will remain confidential until an official release of the findings authorised by both the UK Minister for Science and Innovation and the Director General of ESA. All members will sign a non-disclosure agreement.

Membership:

R. Bonnefoy	*Chairman, ESA*
D. Link	*Deputy Chairman, UK*
J. Casani	*NASA/JPL, USA*
V.A. Vorontsov	*Babakin Space Centre, Russia*
F. Engström	*Consultant*
P. Wolf	*Consultant*
R. Jude	*Consultant*
B. Patti	*ESA*
C. Jones	*ESA, Secretary*

Schedule

The Commission of Inquiry will initiate its work in February 2004 with a presentation by the Beagle 2 and Mars Express programmes/projects together and an initial data package, and the report is expected to be available by the end of March 2004.

2.2 MODUS OPERANDI

In line with its mandate, the Commission has pursued its inquiry into both the programmatic and technical aspects of the Beagle 2 project. The objective throughout has been to capture the lessons learned from Beagle 2 in order to improve future projects.

The programmatic aspects include: ESA's Announcement of Opportunity for Mars landers to be included in the Mars Express mission; the assessment of the lander proposals received by ESA; the approval process for both Beagle 2 and Mars Express within ESA's Science Programme Committee (SPC); Beagle 2's financial and management arrangements; the role played by the UK authorities and ESA senior management; the formal review processes during the project and the commercial and contractual issues.

The technical aspects include all items of the system requirements definition, design, development, testing and in-flight operations of Beagle 2. The Commission is grateful, especially to EADS Astrium (the main Beagle 2 contractor) and the University of Leicester, for assistance through the provision of documentation and briefings, which have been invaluable in aiding the Commission's understanding.

The Commission has not addressed the scientific objectives or the instruments, as they are not considered relevant to the loss of Beagle 2.

The Commission has interviewed the key players in the Beagle 2 project, many of whom are now employed elsewhere, and is grateful for the time which they have donated to this task. The Commission has also engaged technical experts from ESA, NASA and Babarkin Space Centre, Russia to assist with aspects of the Inquiry, eg to undertake specialised analyses, and is grateful for their assistance.

3 BEAGLE 2 OVERVIEW & EVOLUTION

Beagle 2, the lander spacecraft designed to explore the surface and sub-surface of Mars as part of ESA's Mars Express mission, was named to honour the ship involved in the epic voyage made by Charles Darwin and Robert Fitzroy during the years 1831 to 1836 which led to the publication of Darwin's "Origin of Species".

The major aims of the Beagle 2 landing on Mars were to establish whether:

- conditions appropriate to life prevail;
- any evidence for past life has survived;
- global disequilibrium, consistent with an active biology exists.

Beagle 2, with Professor Colin Pillinger of The Open University (UK) as Consortium leader, set out to provide a complete geological and geochemical characterisation of the landing site on Mars. In addition, Beagle 2 was to provide information on the chemistry of the Martian atmosphere and the climatic cycle.

This was to be achieved through a comprehensive suite of scientific instruments which would be activated following Beagle 2's landing on the surface of Mars and the deployment of its solar arrays. The scientific function of each device/experiment are summarised below:

<u>Instrument Functions</u>

Organic chemistry/gas analysis: Open University (UK)	Water detection Abundance of organics Abundance of carbonates Nature of organics Isotopic compositions Detection of atmospheric methane Trace atmospheric analysis Exposure age of rocks
Panoramic Cameras: Mullard Lab. (UK)	Geomorphology, dust properties, soil mechanics atmospheric density
Microscope: MPI-Aeronomie (D)	Texture, petrology
Mössbauer: Darmstadt Tech. Univ. (D)	Oxidation state, rock mineralogy
XRS:	Geochemical composition

Leicester University (UK)	
Gas analysis/XRS:	Crystallisation age of rocks
Environmental sensors: University of Kent (UK)	Temperature, pressure, wind, UV flux, oxidation potential, dust properties
<u>Mechanisms</u>	
Robotic arm and PAW Leicester University (UK)	Sample acquisition
Mole: DLR(D) and Hong-Kong Univ.	Soil mechanics, heat flow.

The total design mass of the scientific instruments was 11.4 kg.

The investigations to be undertaken with these instruments were assessed to be amongst the most important aspects of the study of Mars and were envisaged as "firsts" for Europe. No other Martian lander mission was planning so comprehensive and complete an investigation.

These instruments were carried in a highly-integrated spacecraft providing structural support, thermal control, power, data handling and telecommunications, together with an Entry Descent and Landing System (EDLS). The EDLS consists of a front shield, back cover, pilot parachute, main parachute, gas generator and air-bags. The total design mass of the EDLS was 35.4 kg.

Following an Announcement of Opportunity by ESA and assessment of the scientific potential, engineering and proposed management, Beagle 2 was selected to be a nationally-funded science payload on ESA's Mars Express spacecraft.

The design mass of the complete Beagle 2 lander was 60kg., this being the limit imposed by Mars Express. It was planned to be ejected from the Mars Express spacecraft 5 days prior to its arrival at Mars, using a Spin Up and Ejection Mechanism (SUEM).

The sequence of events for entry, descent and landing was planned as follows. After a high speed entry (5.5km/sec or 20,000km/hr), the probe, protected by its heat shield, decelerates to about Mach 1 in less than 3 minutes, when the pilot chute is deployed. From there on an automatic sequence controls the release of the pilot chute and thermal protection (front shield and back cover), deployment of the main parachute, enabling of the altimeter (RAT), air-bag inflation at 200mtr altitude, and finally release of the lander from the air-bags after coming to rest (following several bounces).

Once on the Martian surface, the lander was designed to right itself and deploy its solar panels for power generation; it was designed to have a nominal lifetime of 6 months on the Martian surface.

Because of its size and mass constraints, Beagle 2 was designed with limited redundancy in its sub-systems, the correct functioning of each being critical to the success of the mission.

4 PROGRAMMATICS

4.1 INTRODUCTION

Mars Express originated from the failure of the Russian Mars 96 mission in which ESA Member States had major contributions. It was proposed in late 1996 that Space Agencies should consider providing a spacecraft which could carry the spare units of the Mars 96 Orbiter instruments to Mars in the 2001 or 2003 launch window and also accommodate surface science instruments. ESA's Space Science Advisory Committee (SSAC) recommended in 1997 that ESA start a quantitative study of such a mission, based on an Orbiter, but with, optionally, the addition of some small landers. This was the genesis of the Mars Express Orbiter, which was an "additional" mission to the Horizons 2000 framework and hence was limited to a Cost at Completion (CAC) of 150 MECU, without any project-level financial contingency. The cost of any instruments and landers would have to be found from outside the ESA science budget.

4.2 PREPARATION/ASSESSMENT OF BEAGLE-2 UP TO MARS EXPRESS APPROVAL

4.2.1 FINDINGS

In October 1997, the Mars Express Science Management Plan was approved by ESA's Science Programme Committee (SPC) including an allocation of 150kg. for lander modules.

In February 1998, the Beagle 2 Consortium: Open University, (Consortium Leader), University of Leicester (project management), Martin Baker Aircraft Company and Matra Marconi Space, responded to an ESA Announcement of Opportunity (AO) for a Mars lander module within a mass of 110kg. including a surface rover.

The Beagle 2 Consortium at that time relied on each partner funding their own activities under a "gentlemens' agreement". There was no customer and no prime contractor. Because of the lack of funding, no classical Phase A had been performed. Some Consortium-based design studies had occurred throughout the latter half of 1997, including presentations to ESA.

In April 1998, the British National Space Centre (BNSC) declared to ESA that it would like to support Beagle 2 and there was "a funding opportunity from central government which could come to fruition in the summer". The Beagle 2 team was trying to raise resources from commercial sources but this had not been confirmed. BNSC believed it was worth keeping open the option to include Beagle 2 in Mars Express for a while longer.

In May 1998, SPC approved the Mars Express payload complement (ESA/SPC(98)17) which did not include a lander.

In June 1998, ESA industrial studies concluded that only 60 kg on Mars Express was available for landers. The Beagle 2 proposal was de-scoped (by removing the rover and by a redesign of the Beagle 2 lander) and re-submitted in July 1998 in response to a revised ESA AO.

The Beagle 2 proposal (plus two other proposals) were assessed by ESA.

The main findings of ESA's engineering assessment of Beagle 2 were:

- The feasibility of the overall system design proposed was marginal in the available time.
- A significant number of risks were identified. These risks were primarily associated with the development and test programmes for certain equipment, all of which needed to be completed in a relatively short time period. Risks included:
    - The separation and eject mechanism, the hinges, and other mechanisms
    - Thermal control
    - Aerodynamics

There was also concern at the minimal mass and schedule margins

The Peer Review Committee (PRC) of SPC, having been briefed on the engineering and financial consequences, the lack of maturity of many Beagle 2 sub-systems and the increased risk for the Mars Express mission, stressed the importance of adding a lander to Mars Express and gave Beagle 2 the highest priority on the basis of its excellent scientific potential.

The PRC recommended (ESA/SPC(98)34) that the following milestones should be met by the Beagle 2 Consortium:

- Demonstration of full funding of Beagle 2 by end October 1998
- Successful close out of all critical areas identified in ESA's engineering assessment of the Beagle 2 proposal at the start of the Phase B of Mars Express
- Meeting the maximum mass of 60 kg for the lander plus 3kg left on the Orbiter with sufficient margin.
- Full agreement with the to-be-appointed (Mars Express) prime contractor on resources, interfaces and programmatics at the start of Phase B

The Solar System Working Group (SSWG) unanimously endorsed the findings of the PRC, being fully aware of the possible extra costs and risks to Mars Express that a lander implied.

The Mars Express baseline mission was re-confirmed by SPC with a Cost at Completion (CAC) of 150 MECU (ESA/SPC(98)34). This CAC covers the satellite, launcher, ground segment and post-launch operations, and the internal ESA costs. The Baseline mission was defined as an Orbiter only mission (without a lander). However, it appears that Beagle 2 was implicitly accepted as a payload, provided there were no costs to the ESA Science programme, giving time for Beagle 2 to meet the conditions above.

The full funding of Beagle 2 was not in place by the end of October 1998.

4.2.2 ASSESSMENT

The concept of treating a lander such as Beagle 2 as a "scientific instrument" on Mars Express was a fundamental error.

Beagle 2 should have been recognised at the outset as a complex spacecraft in its own right requiring development by an organisation with relevant management and space engineering experience, which was likely to be beyond the capability of a PI-led group.

Because of the fundamental impact that any lander would have on the Mars Express mission, the Commission believes that Mars Express and Beagle 2 should have been managed as an integrated mission.

The PRC laid down sensible conditions for the inclusion of Beagle 2 on Mars Express, but there is no evidence that these were followed through.

The Beagle 2 management arrangements at this time were unconventional. There was no clear customer-supplier relationship. No system-level requirements appear to have been generated. The Commission concurs with the PRC's recommendation that a more efficient management structure was needed.

The lack of guaranteed UK funding for the Beagle 2 mission at this time (October 98) did not appear to be a major consideration. The Commission finds this to be a significant weakness in a project which would have required an early and vigorous start to its development programme to remove the shortcomings identified in the assessment of the Beagle 2 proposal.

Recommendation 1

Future lander missions should be under the responsibility of an Agency with appropriate capability and resources to manage it. The lander/orbiter mission should be managed as an integrated whole. Nationally-funded science instruments should be included in the lander on the same basis as on the orbiter.

Recommendation 2

For future science payloads which are critical to overall mission success or have a very high public profile, the ESA Executive should make a formal, comprehensive assessment of all aspects of proposals including technical, management and finance, and advise SPC accordingly before acceptance. If the assessment is not positive, ESA should advise the SPC not to accept the proposal.

4.3 APPROVAL OF BEAGLE 2 AS A PAYLOAD ON MARS EXPRESS

4.3.1 FINDINGS

In January 1999, the UK Particle Physics and Astronomy Research Council (PPARC) reviewed the Beagle 2 and assessed its potential scientific output as being in the highest category. PPARC agreed to contribute £2.7M to the Beagle 2 science instruments in July 1999. At that time, the estimated industrial CAC excluding the scientific payload, was £24M. The financial contribution of the Beagle 2 partners up to the end of Phase B was some £6M. The remaining £18M was to be covered by other funding sources

A Preliminary Design Review (PDR), led by the Mars Express Prime contractor, took place in October 1999, but was largely concerned with the interfaces between Mars Express and Beagle 2. ESA then undertook a System & Engineering Review (SERT) of Beagle 2 at the request of

SPC in order to confirm that Beagle 2 was ready to enter Phase C/D. The major findings reported to SPC were:

- Impressive progress had been made during Phase B;
- No showstoppers were identified;
- A number of areas were identified where a significant amount of work was needed in a short time if Phase C/D was to start on schedule;
- A number of aspects of the Entry Descent and Landing System were not clear from the data package. However, no main problems were anticipated in these areas;
- Mass was critical with only 1% margin, and a mass reduction exercise should be performed;
- The Beagle 2 lander was considered to be sufficiently mature to allow it to progress to Phase C/D, provided that the points raised in the SERT report were resolved.

In addition, ESA reported that “Phase C/D funding appears to be under control”.

In August 1999, the Department of Trade and Industry (DTI) agreed to provide a Grant of £5M to Astrium (ex. MMS) to consolidate the mission feasibility. The approval rested on three findings:

- ESA’s assessment of the scientific merit of Beagle 2;
- PPARC’s assessment of the Beagle 2 scientific outputs;
- Consistency with DTI’s industrial criteria.

This grant, ultimately awarded in January 2000, was to be shared with MBA, but there was no contract between Astrium and MBA. The overall management arrangements for Beagle 2 remained unchanged.

SPC confirmed the selection of Beagle 2 following the report of the SERT (ESA/SPC (99)32). At this time, the total Government funding in place was £7.7M (£2.7M + £5M), the Consortium contribution was £6M but the estimated industrial CAC remained £24M - leaving £13M still to be financed. The funding guarantee requested by SPC still had not been confirmed.

4.3.2 ASSESSMENT

The Commission’s assessment is that at this time there was insufficient guaranteed funding available for a timely implementation of the C/D Phase. The prospect of securing significant project funding from private sources should have been thoroughly and independently assessed.

Beagle 2 was not treated as required, namely a complex, risky project which would require consistent funding and effective management if it was to be successful.

The Consortium's assertion that the required additional funding would become available later was not an adequate basis to continue the programme. The piecemeal approach to the provision of funding as happened in Beagle 2 exacerbated the difficulties inherent in the development and unduly increased the risks.

The Consortium should have had a management structure which implemented a normal project review cycle encompassing the overall Beagle 2 system.

The SERT Review performed by ESA was not comprehensive:

- There was limited review of Beagle 2 system-level requirements

- The Entry, Landing and Descent System (EDLS), particularly parachutes and air-bags, appears not to have been fully reviewed because of lack of clarity in the data package and absence of appropriate experts in the review team.

It is difficult for the Commission to agree with the review conclusion that there were no major showstoppers – this was simply not known in some crucial areas. In this respect, it was an inadequate basis to support the approval to enter into the C/D phase.

Furthermore, the SERT did not report on the close out of the findings of the initial ESA assessment of the Beagle 2 proposal.

The SPC should not have confirmed the selection, given the failure of the Consortium to comply with the recommendations of the PRC. The ESA Executive should have followed through on the recommendations, and advised SPC accordingly.

Recommendation 3

Sponsoring Agencies of nationally-funded contributions to ESA projects should ensure that the required financing is committed at the outset to meet the estimated Cost at Completion and require that a structured development programme is established.

Recommendation 4

In addition to the ESA-led reviews of interfaces, formal Project Reviews of nationally-funded projects should be undertaken by the sponsoring Agency to a standard agreed with ESA and should cover the entire project.

4.4 DEVELOPMENT - SPC APPROVAL (NOV 99) TO SPC ADDITIONAL FUNDING (NOV 00)

4.4.1 FINDINGS

The development of the project continued using a mixture of Government finance (noted above) and the Consortium's own internal resources. In parallel, the Consortium leader was exploring with M&C Saatchi, sponsorship funding from commercial entities. Although the advice from Saatchi was very positive, no financial commitments to the development phase were forthcoming from commercial entities outside the Beagle 2 partnership.

In July 2000, having failed to raise any external private funding guarantees, Saatchi advised the Beagle 2 project, to request temporary financial underwriting from the UK Government and the Consortium, because of "cash-flow problems". A further £12M was approved as follows:

- £5M from DTI/OST
- £3.5M from Astrium
- £3.5M from the Open University

An independent Review of Beagle 2 was commissioned in September 2000 by ESA's D/Science. This review was chaired by J. Casani from NASA and included ESA, NASA and BNSC personnel. The major findings of the Casani Review were:

- Beagle 2 had only become a Space Science project to Mars through the drive and enthusiasm of Colin Pillinger and his team;
- The management structure of Beagle 2 was complex, reflecting the nature of the Beagle 2 Consortium and there were multiple lines of accountability or authority;
- At best, the management arrangement was fragile and could work only so long as the shared interests of the parties did not collide with the corporate interests of the parties;
- Although the project had produced a risk-management plan, risk management in the classical sense, was virtually non existent in Beagle 2 because, in the absence of margins, there was no effective means to mitigate risk;
- The mass of the lander was critical. Aggressive and immediate action should be taken to increase the mass allocation (or descope Beagle 2 functionality) to correct the deficiencies identified;
- The schedule contingency was inadequate for a project requiring major new payload developments, development of a re-entry system and designing for the Mars environment;
- The Entry Descent and Landing System development plan was not robust;
- The project was challenging but doable if the deficiencies highlighted in the Review report were addressed.

In September 2000, the UK Under Secretary of State for Science wrote to the ESA Director General inviting ESA to join the Beagle 2 partnership with the aim of strengthening the financial and managerial foundations of the project. The new CAC reported to SPC was £34.5M (including a contingency of £5.5M). SPC agreed in November 2000 (ESA/SPC(2000)34, rev.1 and ESA/SPC(2000)36 rev.2) to expenditure of 24.2M€ on Beagle 2 under the conditions of:

- An increased participation of the European scientific community in Beagle 2;
- An increased oversight role for ESA by contracting with industry for the following work packages "considered to be the most appropriate":
  - The Entry Descent and Landing System
  - The system-level Assembly Integration and Verification tasks
  - The communications link between the Beagle 2 lander and the Mars Express and NASA 01 spacecraft.
- Recompense by the UK of 16 M€ to the ESA science programme.

4.4.2 ASSESSMENT

During this period, the project suffered from inadequate financial estimating and control within the Consortium. The immediate needs were met by further underwriting by Government and the Beagle 2 partners, but the project's CAC was consistently under-stated.

ESA worked hard to obtain the requested financial support from SPC, which included a requirement for ESA to put in place and manage an industrial contract for key aspects of Beagle 2, including EDLS work packages.

The Casani report, whilst praising the Beagle 2 technical team, was highly critical of the project status. There is evidence of how the Beagle 2 Consortium addressed a few of the Casani technical recommendations, but the Commission considers that insufficient corrective actions were taken on any of the major issues identified. In particular, BNSC and ESA management did not address at this time the organisational shortcomings identified by Casani.

Recommendation 5

When an independent review of a nationally-funded project, such as the Casani review of Beagle 2, is commissioned, it is essential that ESA and the Sponsoring Agency ensure that its recommendations are properly dispositioned and those which are agreed are actioned and followed up through a formal process.

4.5 DEVELOPMENT - FROM NOVEMBER 2000 TO AUGUST 2001

4.5.1 FINDINGS

ESA placed an industrial contract of value 16M€ (£10M) with Astrium in December 2000 which did not explicitly include the development of the EDLS or the other specific work packages mentioned above.

In June 2001, MBA announced their intention to withdraw from the Beagle 2 project due to irreconcilable commercial differences with Astrium. Up to this time there was no contract in place between Astrium and MBA, who were working on short-term financial authorisations from Astrium.

The project requested additional underwriting from the UK Government in July 2001 and announced a new industrial CAC of £42.5M. The project came close to termination, which resulted in a near-cessation of activities for several weeks. Eventually, further Government and Consortium funding was agreed as follows:

- £4.3M from DTI
- £4M from OST
- £2.6M from Open Univ.

The UK authorities remained enthusiastic supporters of the project. They insisted that there should be a single industrial Prime Contractor. The funding was provided on condition that Astrium accepted a Firm Fixed Price contract for Beagle 2 and accepted the risk of any further cost increases. At this point M&C Saatchi were still under contract to secure the sums previously under-written, but had expressed pessimism due to the down-turn in the world economy.

Astrium proceeded to take over the role of MBA, including novating contracts from MBA to Astrium. Some MBA staff were engaged as consultants to Astrium. The key US sub-contractors on the air-bag and gassing systems insisted on remaining on cost-plus contracts.

A Heads of Agreement was drawn up in July 2001 which set out the various responsibilities of the parties - Astrium, BNSC, ESA and the OU. BNSC would act as the lead public customer. ESA's responsibilities included: assisting BNSC in negotiating a fixed-price contract with Astrium and thereafter monitoring schedule and technical progress, partly funding the aseptic planetary protection facility, and supporting drop tests in the USA pursuant to existing ESA/NASA agreements. From this time, BNSC was looking to ESA to advise on risks to the project.

By reducing the number of models and introducing a new and complicated testing philosophy, a new schedule was agreed leading to delivery of the lander in January 2003, with an overall margin of 6 working days.

Astrium now put a larger team onto the project. The progress was accelerated in many areas in order to meet the schedule. Astrium acknowledged to the Commission that not until after July 2001 did they start to do technical work in earnest.

ESA recorded internally its scepticism on the revised Beagle 2 programme.
" By far the most critical items in the Beagle-2 programme are the deliveries from sub-contractors…….. for which:

- No specific requirements seem to exist;
- No evidenced specifications, schedules, and or design and development plans have been demonstrated to exist;
- Not all contractual agreements have been made yet (at least not for all sub-contracts)."

4.5.2 ASSESSMENT

It is evident over this period that the conditions for ESA's engagement in the project had not been fulfilled. ESA did not contract with industry for the EDLS, or the other identified activities. The Commission has been informed that ESA and Astrium were unable to reach agreement on a contract for the EDLS due to commercial differences between MBA and Astrium, and in any case the funding available did not match the estimated cost of the EDLS (£16M). The ESA contract did not include the expected level of oversight or management by ESA. Instead, ESA contracted with Astrium for payment on achievement of key milestones. Considering the strong position which SPC had taken on this aspect, SPC should have been informed of this situation, and been asked for their guidance.

Astrium established very rapidly a large team of senior engineers under the direction of a new project manager to meet the challenging Beagle 2 schedule. They also took over the management of the EDLS, but they had little experience in this critical field. They believed that the EDLS was based on previously-qualified technology, but found this not to be the case. They arranged for the support of ex-MBA staff; however, support from the two leading MBA system designers was limited. The limitations of their involvement was to prove crucial during the remaining development, when EDLS system-level problems arose.

The Heads of Agreement resolved the question of the customer-contractor relationship, but some three years into the project, and finally provided funds to match a more realistic CAC. But much time had been lost through the piecemeal nature of the funding to date, which exacerbated the schedule and testing problems identified by Casani one year earlier. The schedule margin was effectively zero even after the change in the model and testing philosophy, which, in the Commission's view, itself increased the overall risk to the project.

Internally, ESA was reflecting at this time (July 2001) on whether the Beagle 2 project should proceed. The Commission's assessment is that ESA should have communicated clearly to BNSC its reservations about the viability of the project, but did not.

Astrium agreed to accept a firm fixed price contract, funded by BNSC, with a fixed delivery date, which included the activities formerly under MBA. The Commission's view is that the full implications of this were not fully understood by BNSC or Astrium at the time.

The firm fixed price contract provided assurance to BNSC that Beagle 2 would be delivered within the cost ceiling, but implicitly acknowledged that the content of the programme could be adjusted to meet the cost and schedule constraints. In the Commission's opinion, BNSC and Astrium had agreed a "fixed price, variable scope" contract. For example, the Commission learned of instances where elements of the test programme were descoped or deleted as necessary to meet the schedule. In these circumstances increased project risk was inevitable. Adding resources, manpower or additional test articles, which could have been applied to keep the test programme intact, was not an option in the fixed price environment.

Recommendation 6

For future projects, Heads of Agreement or similar formal arrangements between cooperating entities, ESA and national sponsors, should be put in place at the outset of projects and should include formal consultations at key stages of the project to jointly consider its status.

Recommendation 7

Fixed price contracting should be avoided solely as a mechanism for controlling costs, and used only where the sponsor and contractor are in alignment on the requirements and scope of the work and the sharing of risks between them. Both parties should be confident that the contractor has sufficient margins to manage his uncertainties and risks.

4.6 SUMMER 2001 TO LAUNCH

4.6.1 FINDINGS

The schedule of delivery of Beagle 2 to Mars Express remained the top concern of the Beagle 2 team and UK authorities, and planned tests were transferred to other models or descoped to maintain schedule. The ESA priority was to safeguard the Mars Express mission and hence there was great emphasis on the qualification of the ejection mechanism (SUEM).

Astrium deployed a large team (134 work-years over 18 months) plus some 200 full-time equivalent staff in sub-contractors. They faced and overcame a wide range of difficulties through hard work and dedication. ESA considered the Astrium-led Beagle 2 team to be very good. Nevertheless, because they believed the risk of Beagle 2 not meeting the delivery date was so high, ESA prepared two alternative launch scenarios, with and without Beagle 2.

The CDR Close-Out Review occurred in March 2002. This was a more comprehensive review of Beagle 2, encompassing more than the interfaces with Mars Express, by reviewers independent of the project. The criticality of the air-bag system testing was highlighted; however the quality of the work on the EDLS was stated to be outstanding.

Within 3-4 months of the CDR close-out, Astrium informed the Beagle 2 Board that there was need to re-design the EDLS to reduce the landing velocity and this would require a new, larger main parachute. ESA advised that this development was too risky in the remaining timescale. The Beagle 2 Board however, following advice from the UK Ministry of Defence and the Deutsche Luft und Raumfahrt (DLR) decided to go ahead with the new parachute development. A development programme, funded by £1.5M from the BNSC, outside the main Astrium contract, and from Astrium internal funding, was put in place. BNSC and the Beagle 2 Board assessed the risk of this programme to be high.

Between July and mid-October 2002 the new parachute was designed, manufactured, tested and delivered. A CDR on the parachute was held in September involving Astrium and BNSC. ESA declined to participate.

The Beagle 2 flight model was delivered to Astrium, Toulouse, the Mars Express Prime contractor, in Feb 2003.

The Flight Acceptance Review (FAR) report (March 2003) identified no showstoppers. The main concern was the late and missing documentation in the Beagle 2 data package.

The FAR Closeout Review (April 2003) confirmed that the Beagle 2/Mars Express interface qualification was successfully achieved. It also highlighted:

- Risk of slight instrument damage due to overpressurisation;
- Concern on the spread of ejection parameters;
- The need to finalise the Mars surface operations strategy.

4.6.2 ASSESSMENT

This was a period of intense activity by Astrium and its subcontractors. They overcame many difficulties and, considering the situation in August 2001, it was almost a miracle that Beagle 2 was delivered more or less to schedule.

It is clear that the schedule constraints noted by Casani and others led to an attenuated testing programme. The whole programme was concentrated on the delivery of Beagle 2. In the opinion of the Commission, and contrary to the conclusion of the CDR close-out review, the risk of mission failure had grown considerably.

The air-bag failures and the subsequent decision to redesign the main parachute compounded the risk further, and this was recognised within the Consortium. But it did not result in a proper preparation of public perception of the likely success of the mission.

It was unfortunately still the case that ESA and BNSC were viewing Beagle 2 from differing perspectives. No concerted actions seem to have been taken by ESA and BNSC to prepare for dealing with the media in the event of failure.

Recommendation 8

For future high-profile/ high-risk projects, ESA and any Sponsoring Agency should manage the expectations of the outcome of the project in a balanced and objective way to prepare for both success and failure.

5 TECHNICAL

5.1 DEVELOPMENT APPROACH

5.1.1 SYSTEM LEVEL DOCUMENTATION

Findings

No system-level Requirements, Specification or Design Report documents for the complete Beagle 2 system were generated by the initial Consortium - and this has remained the case. Within their Beagle 2 "consensus" management structure, they were able to define directly all the necessary interfaces between their respective areas of responsibility. The documentation required for such a development therefore only exists at the lower levels when a "customer" was defined, either through a commercial contract or in-house task assignment.

Assessment:

In the original, entirely self-funding environment the omission of these documents can be understood - it was a low cost approach - especially when some Partners wished to guard closely some know-how or were constrained in release of information.

The missing system-level documentation resulted in the project reviews that were held, being unable to assess the system-level design, but concentrating only on the subsystem-level. Furthermore, the effectiveness of reviews was compromised by limitation in access to information and relevant expertise of independent reviewers.

The Commission also noted that the absence of system-level documentation prevented the generation and maintenance of the system-level baseline in a documented form throughout the programme. It also impaired the Commission's own ability to perform a thorough investigation.

The lack of system documentation became even more critical after the departure of MBA, since apparently only a limited set of documentation was transferred to the Astrium overall system lead. Furthermore the departure of MBA left the Beagle 2 Consortium without a core system team with previous experience on planetary re-entry missions.

The Commission believes that this situation has led to significant design and verifications issues being overlooked, some of which could have led to the loss of mission:

- Change of the main parachute drag and gliding characteristic, with related impact on the ballistic coefficient ratio between the back cover under the pilot chute and the lander under the main parachute.(Section 5.4.4)
- Change of the main parachute’s gliding characteristic with the related probability of collision with the rebounding air-bag/lander. (Section 5.4.6)
- Change of probe mass and entry path angle with related impact on Beagle 2 entry dynamics (Section 5.4.3)
- Extension of time duration under the pilot chute with related impact on the front shield temperature excursion (Section 5.4.2)

These are covered in detail in the chapter covering the individual sub-system assessments.

Recommendation 9

At the start of a programme the funding authority(ies) should require that there is system-level documentation. This is necessary to provide all partners with the technical requirements for the project and sufficient design description and justification such that the margins and risks being taken in each partner's area of responsibility are visible.

5.1.2 RISK MANAGEMENT AND MARGINS

Findings

As highlighted in the Casani review, classical risk management at system level was not possible; because adequate mass and volume margins, as well as funding and schedule flexibility, never existed.

Assessment:

The absence of system-level documentation meant that none of the Partners had an overview of all the risks, and hence of potential imbalance of the risks and margins as they evolved during the development. In addition, if one partner withdrew the remaining partners would be left without an overall rationale, and documentation, for the risks and margins

This was Astrium's situation when MBA withdrew - they remained without an overall risk/margins rationale when faced with later development problems which necessitated changes of several critical parameters which affected the overall risk.

5.2 SYSTEM DESIGN

5.2.1 DESIGN ROBUSTNESS

Findings

The Beagle 2 document Failure Modes Effect & Criticality Analysis (FMECA) records more than 30 Single Point Failures (SPF).

Assessment:

The Commission considers that Beagle 2 is very innovative but risky design to cope with the extremely stringent mass and volume constraints and the very ambitious science objectives. While the string of so many SPF’s was recognised from the time of the initial proposal, the consequent risk was not mitigated by a thorough testing and verification programme (see below).

Recommendation 10

Future planetary missions should be designed with robust margins to cope with the inherent uncertainties, and they should not be initiated without adequate and timely resources to achieve that.

5.2.2 TELEMETRY

Findings

There was no telemetry from separation until completion of deployment.

Assessment:

The lack of telemetry prevents confirmation of a healthy spacecraft prior to and during entry and descent. It has drastically limited this failure investigation, and precludes deriving lessons learned for future missions.

Previous missions, including the Russian Mars96 and NASA Mars98, also did not have a transmit capability during entry and descent. This was a critical finding of the Mars98 failure review, and resulted in extensive effort to provide it on the NASA MER mission.

Recommendation 11

Future planetary entry missions should include a minimum telemetry of critical performance measurements and spacecraft health status during mission critical phases such as entry and descent.

5.2.3 COMMUNICATIONS SYSTEM

Findings

The communication transceiver was controlled by on-board software.

Assessment:

In order to reduce mass and power consumption, the design of communications system relied on the on-board scheduler. No direct commanding, without software decoding, was possible.
The design of the Beagle 2 antennas did not provide a communications path if the lander was not fully deployed.

The design precludes:
- Resetting of the lander in case of software crash (no direct TC);
- Commanding of the probe deployment if not fully terminated;
- Patching the software through low level commanding;
- Over-ruling some automatic programmed communications inhibitions or decisions.

Recommendation 12

For future planetary entry missions, a more robust communications system should be used, allowing direct commanding of the lander for essential actuations and resets without software involvement - enabling recoveries in catastrophic situations.

5.3 SYSTEM-LEVEL TESTING

5.3.1 TESTING FOR LOW FREQUENCY SHOCK AND PYROTECHNICS SHOCK

Findings

Survival shock tests were performed at equipment level based on analytically-derived medium and long duration shocks. However:

- No landing shock testing was performed at system level for the Beagle 2 lander.
- No test of the complete descent sequence including actual pyro firings was performed with the complete system.
- No tests were performed to demonstrate the structural integrity of the Beagle 2 local structure after the mortar for pilot parachute deployment was fired.

Assessment:

System-level pyro-shock testing is particularly important because shock levels are notoriously difficult to model. The unit and PCB level tests that were performed, covered only the analytically-derived medium and long duration shocks corresponding to the estimated shock levels for air-bag inflation and drop-onto-surface, respectively, but omitted the high frequency shocks generated by the firing of the 3 aero-shell clamp separation devices. Tests at higher integration levels were planned but had to be omitted at a late stage in order to meet the launch/delivery schedule.

The Commission believes that, due to their mounting directly on the primary structure, the Beagle electronics were exposed to severe shocks throughout the various mission phases, with consequences that could have ranged from failure of some components to reset and reboot of the software during the critical deployment phase.

The fact that no testing was performed at system level to qualify and verify the Beagle 2 performance capability under such environments is considered by the Commission an inadequate verification of the design.

Additional funding, made available sufficiently early in the programme could have provided an adequate model to be tested, decoupled from the schedule of the FM integration.

Recommendation 13

Planetary probe missions involving high-level shocks from pyros and other events should undergo representative shock environmental testing at system level.

5.3.2 FUNCTIONAL DEPLOYMENT TESTING

Findings

Such a test, presumably from a high altitude drop, was not considered within the scope of the programme, primarily for cost reasons.

Assessment:

It is common practice in planetary probe programmes, to perform a verification of the deployment sequence by a drop test at high altitude in representative dynamic pressure and Reynold's number conditions. Although Earth atmospheric conditions do not allow a fully representative simulation of Martian conditions, the lack of a high altitude drop test aiming at verifying the complex deployment sequence of Beagle 2 is considered by the Commission to be a major omission.

The severely reduced margins in some area of the design (eg ballistic factors ratio), together with the adoption of minimum-mass design solutions (single mechanism for back cover and front shield release) should have necessitated a verification by test of the Beagle 2 deployment sequence.

However, the time scale required for planning and performing this test would have required it to be included from the beginning, based on the results of a classical phase B, where the major system risks would have been identified. The Commission believes that, with the selected design, this test should have been mandatory.

Recommendation 14

Adequate and realistic deployment tests should be performed, and sufficient time and resources must be available in the development of a new planetary mission.

5.4 SUBSYSTEM DESIGN AND VERIFICATION PROGRAMME

In the following section the Commission has examined those subsystems whose design and/or verification could have put at risk a successful entry, descent and landing.

5.4.1 ELECTRICAL

5.4.1.1 Probe Software (PSW)

Findings

There was no independent SW validation (ISV).

The SW design concept is based on an auto-reboot (which takes not more than 3 secs), whenever an error or hang-up occurred, back to the continuously updated "stored context".

Assessment:

Although testing of the PSW was not independently validated, the Commission believes that it was adequate.

The re-boot concept deals adequately with Single Event Upsets (SEU) which might occur during the 5 days operations (Coast phase). The possibility of radiation damage during the Cruise period (which included a record solar storm) is considered unlikely since the total dose has been shown to be within the electronic parts specification.

The Commission understands that Independent Software Validation is now a mandatory requirement for mission critical software in all new ESA missions, and supports this.

5.4.1.2 Electrical Wiring

Findings

To save mass, a minimum number of connectors are used to complete the wiring of the different units. Connectors were used where imperative for Assembly, Integration and Verification (AIV).

No consolidated system-level wiring diagrams of the Beagle 2 exist.

Assessment:

This approach is very unusual, and places significant responsibility on the Flight Model (FM) integration engineers who must "manufacture to drawing" in the difficult physical circumstances of the Aseptic Assembly Facility - inside which, paper procedures and drawings were not allowed,- and under extreme schedule pressure.

Recommendation 15

Elimination of internal connectors for mass saving should be avoided if at all possible. But if unavoidable, a stringent system of check and independent cross-check should be followed during the final wiring operation.

5.4.2 ENTRY THERMAL PROTECTION

Findings

Sizing of the Thermal Protection System (TPS) was based on the peak and integrated heat fluxes predicted by the entry simulation during the early design phase when the range of flight path angle was larger than the final values.

No re-verification of the TPS was performed after the time under the pilot chute was extended.

Assessment:

The margins used in the design, although not properly documented, were judged adequate by the Commission. In addition, two major design drivers changed during the development phase, namely the ballistic coefficient and the maximum entry path angle. Although these changes compensated each other in principle, this was not quantified or documented as part of the system baseline maintenance.

In addition, the system baseline was also not re-assessed following the delayed release of the pilot chute. However, the Commission believes that the entry thermal protection is not a likely cause for the Beagle 2 loss.

5.4.3 ENTRY DETECTION

Findings

The design approach to detect T zero using the g-profile of the deceleration curve is conventional.

There is no back-up for the detection chain, which reacts on the input from either of the two redundant accelerometers.

Assessment:

The absence of majority voting on 3 accelerometers is not considered sufficiently robust for this critical event, and furthermore there is no back-up.

Recommendation 16

A back-up for the entry detection event (T0) must be included in the design of planetary entry probes.

5.4.4 BACK COVER - FRONT SHIELD RELEASE

Finding 1

The back cover and front shield are not released sequentially, but simultaneously, by a single pyro event (at 3 locations).

Assessment:

There is an inherent danger of uncontrolled re-contact between the (just-released) front shield and the lander main body, before the main parachute can provide adequate drag to separate the two items. During the time (1 - 4 sec) before the main parachute provides sufficient drag to separate them, the front shield could be displaced, either by the bolt release shock or disturbances transmitted by the main parachute extraction, and may re-contact due to dynamic pressure and damage the lander main body.

Finding 2

The change of the drag and gliding characteristics of the redesigned main parachute reduced the difference (ie. margin) of the ballistic coefficients between the back cover under the pilot chute on the one side and the lander under the main parachute on the other side.

Assessment:

Before the redesign of the main parachute (see also section 5.4.5. for detailed assessment), the requirement of no re-contact between the back cover and the main parachute was achieved through two design features:

- The ratio between ballistic coefficient of back cover + pilot chute and lander + main parachute was designed to be equal to 1 in the worst case (i.e. including all the identified uncertainties in combination).
- The main parachute had gliding characteristics.

The coefficient ratio should be large enough to ensure that the back cover could not catch up with the main parachute. Equal ballistic coefficients ensure that the two bodies will fall at the same velocity. The gliding feature ensured that while the back cover would have kept descending vertically, the main parachute would achieve a lateral relative motion between the two elements, generating a further clearance in order to avoid re-contact.

A ballistic coefficient ratio of 1 is considered by the Commission a very risky design, providing essentially no margin, - but recognised as being due to the very stringent mass requirements.

The introduction of a different main parachute having higher drag and no gliding characteristic eliminated the two design features needed to avoid re-contact. The Commission estimates that the ballistic coefficient ratio between the two assemblies is between 2 and 3, causing the back cover to fall faster.

An attachment tie was introduced to disturb the orientation of the back cover in order to generate a relative lateral velocity between the two bodies and avoid re-contact. The Commission does not consider that this design feature could have achieved its objective, because the motion of the back cover/pilot chute assembly remains dominated by the force exerted by the pilot chute.

A full modelling of the motions of the bodies in this situation has not been performed and in addition no testing was done.

This feature of the Beagle 2 design is considered insufficient to guarantee no collision between back cover and main parachute, and could possibly have led to mission loss.

Recommendation 17

Future planetary entry missions should include a release of the back cover and front shield which is aerodynamically stable and analytically predictable to avoid uncontrolled re-contact of front shield with the lander.

Recommendation 18

Sufficient difference between ballistic coefficients of all separated items, eg. the back cover assembly and the main parachute, or other positive means must be ensured to exclude collision after separation.

5.4.5 MAIN PARACHUTE

Findings

Very late in the development programme (less than 1 year before delivery), failures of the air-bag drop tests resulted in the need for a new main parachute design.

The strength qualification, 20% over design load, was performed in ground testing behind tow-truck. The design load used a 10% margin with respect to the predicted load. The predicted load was based on modelling of the parachute opening. The validation of this modelling of the parachute opening was based on heritage and literature data and the air-drop test.

Assessment:

Astrium assembled a team with considerable experience in an extremely short time, and their efforts to design, develop, test and delivery the new main parachute are exceptional. The canopy design chosen, "ring-sail" type, has heritage in several atmospheric entry missions. For mass reasons a new fabric was chosen. Because of the tight schedule and for reasons of export license, governed by US International Traffic in Arms Regulations (ITAR), a new manufacturing company was selected for the Flight Model, which did not have previous parachute experience. Within the time and budget available, the testing programme was limited, and given this limitation, the design margins are considered insufficient.

Concerning strength qualification, it is universally acknowledged that great care, ie. generous margins, should always be taken when using data as "heritage" when it is from a different parachute. Furthermore, the air-drop test at low altitude was not representative of opening in the Mars density and velocity regime. Hence the predicted loads against which the parachute was qualified should have included larger margins, and in this respect the qualification is considered minimal.

Concerning the drag coefficient (Cd) value used to calculate the final descent velocity - which is critical for air-bag performance, - the non-representativity noted above also affected the validation of the Cd value. The Cd value was based on the air-drop tests and heritage/literature data, and Monte Carlo simulation was applied, but no clear margin policy is evident.

The Commission considers that the drag coefficient of 1.04 adopted by the Beagle 2 engineers is too optimistic. A value in the range of 0.8 to 0.9 is more likely. This lower value would lead to a higher final velocity, potentially exceeding the capabilities of the air-bags, and providing only a small gain compared to the old parachute performance. Other aspects of the main parachute operation give less concern, namely;
- extraction of the packed parachute from its bag
- inflation in the high speed regime
- stability after inflation

Overall, the Commission's assessment is that this very quick development programme for the main parachute did not include an adequate qualification.

Additional financial resources would probably not have made a significant difference to the final confidence in the design. Adequate confidence in the design would have required completely different testing, requiring much more time than was available.

Given this time/testing constraint, the design should have had much larger margins. This was not possible because the volume available in the back cover was a limitation, and because of its location, any additional mass to be granted by Mars Express would have reduced the margin on aerodynamic stability of the probe during the entry.

The assumption on the Cd coefficient 1.04 is considered unrealistic if not proven by representative testing - to the point of putting into question the exceptional effort undertaken by the development team in order to solve the air-bag problem.

5.4.6 AIR-BAG REBOUND INTO MAIN PARACHUTE

Findings

The original strop length under the main parachute was approx. 100mtr. (using a "strop-extender" which deployed after the initial inflation was achieved).

The feature was deleted during the design phase, and the parachute changed to a gliding type - allowing a short strop (approx. 30mtr) to be used while still avoid rebound into the main parachute.

When the main parachute diameter was changed to reduce the descent velocity after the air-bag test failures, the strop length was retained. The gliding feature was abandoned but the strop extender was not re-introduced. The analysis was not repeated with the revised characteristics.

Assessment:

The absence of both the strop extender and the gliding parachute, effectively eliminated both of the design features intended to prevent air-bag rebound into the main parachute.

Rough estimates based only on design values for descent velocity and coefficient of restitution, predict the air-bag to rebounds up to 28mtr height 4 secs after the first bounce/parachute release event. This clearly implies a real probability of contact and possible entanglement, especially with the re-designed, non-gliding parachute which will normally fall vertically in the absence of wind.

For this reason, other planetary parachute systems have always used much longer strop lengths. The Commission considers that an analysis of the implications of the short strop and the non-gliding parachute should have been made.

The Commission considers this as a possible cause of mission failure.

5.4.7 AIR-BAG

Findings

The initial design was based on a 2.3mtr diameter, low pressure air-bag.

The selected UK contractor had no space experience on air-bags and was replaced by the US company with direct space experience.

To comply with the severe mass requirements, the new contractor proposed a design based on 1.9mtr diameter at higher pressure, and less abrasion layers than the NASA MER mission.

The probability of survival was agreed within the Consortium to be 75%, based on Monte-Carlo simulation.

Following the late change of responsibilities from MBA to Astrium, the scope of the test programme and number of development models were reduced.

During the development, test failures meant that the pressure in the air-bags had to be reduced to 1.6psi.

With the reduced pressure, 3 successful (first bounce) tests were achieved on rock surfaces with descent (and lateral wind) velocities corresponding to approximately nominal value of 16 m/sec plus 10%.

From the spring constant measured in these tests, the actual capability was extrapolated.

Testing for the nominally 10 or 11 subsequent bounces was limited to only one additional "edge-on" test at a lower velocity (10m/sec), corresponding to the orientation with minimum "stroke-out", and again this was used to calculate the spring-constant to extrapolate air-bag actual capability.

Assessment:

The air-bag system was new to European industry and ESA. Its design and testing was effectively only reviewed by independent experts once (2 NASA specialists during the Casani review). The severe mass constraint resulted in inadequate robustness of the design which was not recognised early enough due to the lack of experience.

The limited funding, schedule and test facility availability, together with the later changes of design, led to a reduction of the testing programme, which had already been judged inadequate by the Casani review. For qualifying air-bag performance, dependent on vertical velocity, horizontal velocity, lander orientation, and rock/surface characteristics, many more than 4 tests are required. The NASA and Russian planetary missions each used more than 30 drop tests to establish the air-bag robustness.

The air-bag design was not robust, and the testing programme not sufficient to demonstrate capability, with adequate margins, for a mission critical function.

The Commission considers failure of the air-bags to be a possible cause of mission loss.

Recommendation 19

Adequate competencies in air-bag and parachute technology must be available for future European planetary missions, making best use of existing expertise, e.g. in USA and Russia.

5.4.8 LANDER/AIR-BAG RELEASE

Findings

The "lace-cutting" event, which allows the lander to fall to the surface, is based exclusively on absolute timing.

Assessment:

This event is critical. If too early, the air-bag may be still bouncing and the lander may fall from a height much more than the air-bag radius. If too late, the lander may already be enveloped, inescapably, by the deflating air-bags. The 130sec release timing was reported to be based on:

- the estimated duration of the bouncing phase was 120sec, with a 99% probability based on a Monte-Carlo analysis. A margin of 10sec was added.
- the leak rate of the air-bags (due to the unquantified, but inherent, leaking through its sewn seams).

The Commission considers this a risky design, and a possible cause of failure.

Furthermore, the "guaranteed self-righting" properties of the lander opening device is questioned by the Commission, based on experience with similar designs. There may be initial rest positions which cause the lander to rotate, during hinge operation, into an orientation which does not allow the subsequent deployment of the solar arrays.

5.5 PRODUCT ASSURANCE (PA) AND QUALITY ASSURANCE (QA)

Findings

PA-Safety and QA requirements and rules for Beagle 2 design, development, qualification and flight unit integration and acceptance were applied early by each Beagle 2 Consortium partner, according to his own house rules, later consolidated by Astrium with the company PA/Safety and QA system.

The role of ESA PA/Safety and QA for Beagle 2 was limited to:

- Formal approval, control and inspections of Beagle 2 compliance with Mars Express interfaces.
- Safety submission, covering the period from Beagle 2 integration on Mars Express through until Beagle 2 separation.
- Auditing materials and facilities partially paid for by ESA eg. Aseptic Assembly Facility (AAF) at The Open University.
- Review and concurrence with the Beagle 2 planetary protection/sterilisation programme and results.
- Review and concurrence with all Beagle 2 Non Conformance Reports (NCR's), their dispositions and relevant waivers, submitted by the Consortium, for incorporation into the Mars Express Flight Model acceptance data package.

During final Beagle 2 Proto-Flight Model integration and testing some anomalies occurred (over-pressurisation, wiring errors), which were dispositioned "use-as-is". In one case, related to leakage currents on battery monitoring, the NCR was left open.

Assessment:

From their above-defined formal involvement, ESA PA/Safety and QA staff and inspectors concluded that:

- Astrium in-house procedures were adequate, though not as strict and extensive as ESA's system,
- PA requirements were essentially limited to physical aspects (mechanical, electrical, thermal, Parts/Materials/Processes, etc).
- Assembly procedures were adequate and the Astrium staff for Beagle 2 final integration appeared professional and experienced.

The Commission believes however that Beagle 2 final assembly in the AAF was so constrained by:

- o limitation of staff numbers simultaneously in the facility,
- o no paper allowed in the aseptic area,
- o the miniaturised and highly compact Beagle 2 system, with essentially no connectors or separate electronic boxes,
- o the time pressure,

that the people became more error-prone than during the final integration of a classical satellite flight unit.

The time impact of these assembly constraints - arising from planetary protection requirements - appears to have been initially under-estimated by the Beagle 2 Consortium. It resulted in unusual high time pressure being applied to an unusually complex assembly activity.

6 ANALYSES OF POST-LAUNCH INFORMATION

The Commission has conducted a number of technical analyses in order to assess whether any post-launch information available could indicate a possible cause for, or evidence of, the loss of Beagle 2. Independently, the Beagle 2 project team has performed their own in-depth investigation - some of which will still continue. Some of their preliminary findings have been made available to the Commission, and in the following sections the Commission reports on its own analyses also taking into account the Beagle 2 team's investigations.

Although the Beagle 2 did not transmit any information after its release from Mars Express, some post-launch information were made available to the Commission:

- Updated Martian atmosphere data obtained from the SPICAM instrument on Mars Express and from NASA/JPL
- Mars Express and Beagle 2 telemetry data obtained by ESA/ESOC during the 6 months Cruise phase after launch until Beagle 2 separation.
- Photographs of the separation of Beagle 2 taken by the VMC camera mounted on the Mars Express spacecraft.

6.1 ENTRY PHASE SIMULATION

There is evidence that the actual atmospheric conditions prevailing during the Beagle 2 entry and descent deviated from the models used for the design. The two NASA MER vehicles both landed "long" - beyond the intended location, though still well within the uncertainty ellipse for their landing site. Also, early data from the SPICAM instrument on Mars Express implied a "thinner" atmosphere than the model used for design.

Independent simulations of the probe entry performed for the Commission indicate that the entry mission design was sufficiently robust to tolerate these variations. The Commission's analysis shows that much larger uncertainties in the atmospheric entry conditions would not have resulted in failure of the EDLS to deploy. Hence the Commission concludes that deviation of the atmospheric entry conditions is not a probable failure mode of the mission.

6.2 LANDING SITE ON MARS

Findings

The landing site selection had to be made 2 years prior to launch, in order to protect the mission success probability for Mars Express, and this imposed some constraints upon the Beagle 2 selection.

Assessment:

The Beagle 2 landing site in Isidius Planitia was little known at the time of selection, in particular its surface characteristics (rock size distribution, properties and distribution of slopes, crevasses, etc.) and the prevailing local weather cycle.

More is known today, from NASA spacecraft, but the Commission has not been able to analyse, in the time available, whether the Beagle 2 design assumptions concerning landing site terrain and weather were sufficiently conservative. Furthermore, this would require detailed scientific investigations.

6.3 IN-FLIGHT ANOMALIES

In this section, the Commission assesses known operations anomalies that may be relevant to loss of the Beagle 2 and considers whether they imply a plausible explanation.

6.3.1 OUT-GASSING FORCES

Finding

Following the first post-launch orientation of the +Z face of the Mars Express spacecraft to the Sun, navigation engineers in ESOC observed an un-expected non-gravitational force on the spacecraft, producing 2.5mm/sec. velocity increase. On the assumption that the force was arising from outgassing of Beagle 2 materials via the HEPA* filter into the SUEM enclosure, the Beagle team assessed whether ice could form in the enclosure that might impede the ejection at Mars. Their conclusion was that temperatures within the enclosure would not allow either water vapour or other contaminants to form, and sustain, ice.

The anomalous events continued to occur throughout the months of Cruise phase whenever a face which had previously been in shadow was exposed to solar heating, but they were not formally recorded as operations anomalies. Up to the time of Beagle 2 ejection, the accumulated force component along the line-of-sight to Mars Express had produced a velocity increase of 9.6mm/sec (the actual value must be higher, since the force is perpendicular to the exposed surface). After Beagle 2 release no further events were observed - although the navigation Doppler data is more difficult to analyse for this purpose when in Mars orbit.

(*) – The HEPA filter is a micro-filter which protects Beagle 2 against the ingress of any particulates or micro-organisms, while on Earth, which could then contaminate Mars. It is the only opening from the probe interior.

Assessment:

The Commission has confirmed that:

- the materials of Beagle 2 contained approx. 300gms of water (200gms in the TPS thermal tiles and 100gms in the various fabrics inside the probe);
- the typical outgassing rates (actual measured values for the Beagle 2 materials are not available) would cause out-gassing to continue several months after launch;
- surface temperatures of the +Z face of Mars Express, when in shadow during the Cruise phase, were sufficiently cold (approx. –160C) to cause ice formation;
- modelling of the vapour dispersion over spacecraft surfaces after exiting via gaps in the Multi-Layer Insulation (MLI), predicts as much as 50% would be deposited on the +Z face;
- the accumulated force observed requires the sublimation of approx. 50gms of ice.

The Commission concludes that the non-gravitational forces observed on Mars Express during Cruise phase were due to the sublimation of water ice arising from the out-gassing of materials inside, and covering, the Beagle 2 probe.

6.3.2 SPURIOUS LIGHT POINTS IN VMC IMAGES

Finding

On the first 3 VMC photographs of Beagle 2 departing from Mars Express, several light points are visible; but no loose-parts were intended to result from the ejection.

Assessment:

Detailed examination and enhancement of the images and geometric analysis has confirmed that:

- they are not celestial objects or image detector defects, but real objects;
- in several cases, images of (probably) the same object appear on 3 sequential frames, moving in nearly straight lines;
- the largest object is moving in a plane which passes through the Beagle 2 mounting area;
- a re-construction of the geometry derived from the sequence of images allows to estimate the velocities to be < 10% that of the Beagle 2 ejection (which was 0.3 m/sec);
- based on the apparent size and its estimated distance from the camera, an upper limit of the size of the largest particle is 4mm diameter.

The Commission concludes that they are water ice particles released by the disturbance of the Beagle 2 ejection, having been accumulated on the MLI collar or areas close-by which were not sunlit for a prolonged period during Cruise (eg. in the shadow of the front shield).

6.3.3 VMC IMAGE OF BEAGLE AFTER SEPARATION

Finding;

The first VMC image after separation shows Beagle 2 at 20mtr distance, and the resolution of features within the outline is very poor. However, there is clearly an anomalously bright area within what should be the shadowed part of the back cover.

Assessment:

The object appears to be elongated in the direction of rotation of the Beagle 2, but the long exposure time (500msec) combined with the 15rpm rotation rate of Beagle means that even a bright point of light would appear elongated through 45deg (or, in this case, until it was rotated into shadow).

The MLI covering the back cover is 5 layers (plus Dacron mesh spacers), the outer layer is shiny (aluminised), and the blanket is intended to be "close-fitting". But it is not attached to the back cover at any point on the conical section - only closed on itself at the overlap, and attached to the folded-over edge of the Front shield blanket. Photographs taken immediately prior to launch show quite a looseness overall, and some crinkling of the outer layer.

The "typical" configuration of MLI blankets when in space has seldom been observed, and the centrifugal force due to the 15rpm rotation of Beagle 2, further complicates any assessment. There is not an evident reason for local damage of the MLI at this particular location;

- the TPS covering of the back cover beneath the MLI has no features or devices at this position which could have come loose and bulged or ruptured the MLI,
- it is not in the area around the “collar” which could potentially have been damaged by rupture of local icing during ejection.

On the other hand, it is considered possible that a crinkled area of the outer blanket could have been elevated into the sunlight, especially since the Sun-illumination angle of the back cover is very small at this location.

Consequently the Commission cannot conclude that there is a connection between the image anomaly and the loss of Beagle 2.

6.4 BEAGLE 2 ON MARS

The Commission has been informed of the investigations of the Beagle 2 team and the attempt to locate the Beagle 2 on the Mars surface using photographs taken by the NASA spacecraft currently in orbit. The Commission is not aware that any trace of the Beagle 2 has yet been found.

List of Acronyms

AAF	Aseptic Assembly Facility
AO	Announcement of Opportunity
BNSC	British National Space Centre
CAC	Cost At Completion
CDR	Critical Design Review
DTI	Department of Trade and Industry
EDLS	Entry, Descent and Landing System
ESA	European Space Agency
ESOC	European Space Operations Centre
FAR	Flight Acceptance Review
FM	Flight Model
FMECA	Failure Modes Effects & Criticality Analysis
HEPA	High Efficiency Particulate Air (Filter)
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
MBA	Martin-Baker Aircraft Company
MER	Mars Exploration Rover
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NCR	Non Conformance Reports
OST	Office of Science and Technology
OU	The Open University
PA	Product Assurance
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PFM	Proto-Flight Model
PI	Principal Investigator
PPARC	Particle Physics and Astronomy Research Council
PRC	Peer Review Committee
QA	Quality Assurance
SERT	System & Engineering Review Team
SEU	Single Event Upsets
SPC	Science Programme Committee
SPF	Single Point Failure
SSAC	Space Science Advisory Committee
SUEM	Spin Up and Ejection Mechanism
TPS	Thermal Protection System
VMC	Visual Monitoring Camera